Engineering Structures 158 (2018) 164–174

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

A compact nonlinear dynamic analysis technique for transmission line cascades

Fábio Alminhana[a,c,*], Matthew Mason[a], Faris Albermani[b]

[a] School of Civil Engineering, The University of Queensland, Brisbane, Queensland 4072, Australia
[b] School of Engineering and Technology, Central Queensland University, Ooralea, Mackay, Queensland 4740, Australia
[c] Science and Technology Foundation (CIENTEC), Rio Grande do Sul, Brazil

ARTICLE INFO

Keywords:
Cascades
Transmission lines
Steel lattice towers
Nonlinear analysis
Time-domain dynamic analysis

ABSTRACT

Progressive failures, or cascades, have played a major role in numerous transmission system collapses around the globe during severe wind and ice storms. The failure of a line component overloads the system and initiates a failure sequence that can cause the collapse of many towers. This article describes the development of a special-purpose nonlinear dynamic analysis technique for the modelling of multi-span line sections under progressive failure scenarios. This method performs time-domain analysis based on a central finite difference scheme, adapted for a non-constant time increment. All the main line components are incorporated in the analysis. In particular, a special beam-column element is employed to describe geometric and material nonlinearities of angle members in steel lattice towers. The method is validated using full-scale test results for a single lattice tower and a line section containing seven towers.

1. Introduction

1.1. Background

A transmission line cascade is a difficult-to-control failure sequence of line supports, triggered by the failure of a single or a limited set of line components. Cascade events are commonly classified into three categories depending on the damage pattern, namely: vertical, transverse and longitudinal cascades. Vertical cascades are triggered by the failure of a suspension insulator assembly or its fittings, causing the insulator string to drop creating a *superspan*, i.e., a new span formed by the two spans adjacent to the failed insulator. This overloads insulator assemblies at both ends of the superspan, which can propagate a failure sequence through the remaining line section. The damage caused by this type of cascade is generally confined to insulator strings and conductors.

In transverse cascades the failure sequence is initiated when a line support collapses perpendicular to the transmission line itself. Line angles are created in the supports adjacent to the affected structure, which result in high conductor tensions and induce large unbalanced transverse and longitudinal loads on these supports. Since all conductor phases and shield wires are affected, the structures next to the failed support are drastically overloaded. Localised wind events, such as downbursts and tornadoes, acting on one or more of the line suspension support are the most common triggering event of transverse cascades.

Longitudinal cascades are the most well-known type of transmission line progressive failure. Reports of these cascades date back to the beginning of high voltage electrical transmission, in the early 20th century [1]. The triggering event occurs whenever any of the line components responsible for maintaining tension in the conductors and shield wires fails. The line supports adjacent to the failure location are affected by sudden longitudinal imbalanced loads, which may cause these supports to collapse and overload the next supports. Not all conductors and shield wires are affected by the triggering event, and the intact spans help to withstand the failure propagation. Severe large synoptic wind and ice storms are likely to trigger longitudinal cascades. These events impact a large segment of a transmission line and are able to find the weakest links within the line, such as a conductor with fatigue ruptured strands.

1.2. Prior cascade investigations

Investigations of the structural behaviour of transmission line components during cascade events have been conducted using experimental and numerical approaches. They broadly focused on the determination of the response of a line section to conductor breakage loads, i.e., longitudinal cascades. A limited number also investigated line behaviour during vertical cascades. No comprehensive

* Corresponding author at: School of Civil Engineering, The University of Queensland, Brisbane, Queensland 4072, Australia.
E-mail address: alminhana@gmail.com (F. Alminhana).

https://doi.org/10.1016/j.engstruct.2017.12.039
Received 29 September 2017; Received in revised form 19 December 2017; Accepted 20 December 2017
Available online 28 December 2017

investigation of transverse cascades was found in the literature.

Peabody [2] compiled a catalogue of important full- and small-scale tests on line sections carried out prior to 1997. Alminhana [3] extended this to 2016. Full-scale tests were reported on a range of transmission lines with voltage ranging from 50 to 400 kV. These tests primarily investigated the response of line sections to broken wire loads, aiming to obtain peak dynamic loads (PDLs) and residual static loads (RSLs) to be used as guidelines for the design of line supports to longitudinal loads [4–7]. The tests of Peyrot et al. [8] and Vincent et al. [9] also investigated the line response to the failure of other components, namely insulator string failure, shield wire breakage and support collapse. Investigations using small-scale tests were also primarily concerned with determining PDLs and RSLs during broken wire events. Borges et al. [10] conducted 67 small-scale broken conductor tests on scaled 150 and 220 kV transmission lines. He verified that the conductor impact factor (i.e. ratio between the PDL and the respective initial load) changes linearly with $\sqrt{wL/T_i}$, where w is conductor unit weight, L is the span length and T_i is the initial tension (before the break).

Both in-house software and commercial packages have been employed to investigate the dynamic response of line sections under cascade triggering events. Siddiqui [11] and Thomas [12] were pioneers in the use of time-domain dynamic analysis to obtain the response of transmission line systems subjected to broken wire loads. Given the limited computational resources at that time, they employed simplified models with a reduced number of degrees of freedom. McClure and Tinawi [13] employed the generalised finite element software ADINA [14] to obtain the dynamic response of line sections due to conductor rupture events. They attempted to numerically simulate the results of the small-scale tests presented by Mozer et al. [15]. The main goal was to assess current design criteria for longitudinal loads due to broken conductors, and also to verify ADINA's ability to accurately capturing the scale model test results. McClure was the first researcher to analyse a full line section, including all conductor phases, the shield wires, suspension and dead-end towers [2]. The sections simulated were based on the James Bay 735 kV lines owned by Hydro Quebec (Canada). More recently, Nafie [16] and Kaminski [17] tackled the simulation of line section response under broken wire loads by using a relatively similar approach to Siddiqui and Thomas, however the full modelling of the line supports was also incorporated. The results of these investigations showed that numerical methods can be used to model conductor breakage events with a high degree of accuracy.

1.3. Nonlinear analysis of transmission towers

Albermani [18] pioneered the development of an analysis technique to model the nonlinear response of transmission line steel lattice towers. In his model, linear, geometric, and deformation stiffness matrices are used to simulate the geometric nonlinear behaviour of tower angle members. A lumped plasticity approach in conjunction with a yield surface in the force space is employed to incorporate material nonlinearity. The model is able to predict tower ultimate capacity to static load cases by progressively detecting buckling and yielding in various members.

Jiang et al. [19] developed a computer software to perform second-order direct-analysis of steel lattice towers. The method accounts for both P-δ (member curvature) and P-Δ (frame sideways) effects. The initial equivalent bow imperfection is assumed as a sinusoidal curve with a maximum deflection of $L/300$, where L is the member length. The magnitude of the out-of-plumbness imperfection is adopted as $H/500$, where H is the tower height. Joint effects of bolt slippage and semirigid connections are also incorporated. These are modelled by modifying the stiffness matrix of tower elements to account for dimensionless spring elements at their ends. The software can also perform section capacity checks and is suitable for both static analysis and design of lattice towers.

Lee and McClure [20] derived the formulation of a general three-dimensional L-section beam finite element to predict the response and ultimate capacity of angle members of steel lattice towers. The formulation considers load eccentricities, boundary conditions, geometric and material nonlinearities. This element is very attractive for elasto-plastic large deformation analysis in comparison with shell finite element models, as it requires less modelling and computational effort.

1.4. Overview of this study

In this article, a compact nonlinear time-domain dynamic analysis technique to obtain the response of multi-span transmission line sections under time-dependent forces and boundary conditions is presented. The method lends itself to the prediction of response of line sections during cascades, and can simulate all three types of transmission line progressive failures.

All the main line components are modelled, i.e. conductors, shield wires, insulator assemblies and supports. A special beam-column element is used to simulate material and geometric nonlinearities exhibited by the main members of the steel lattice towers. The formulation can detect element buckling and the formation of plastic hinges using a lumped plasticity approach. This permits post-elastic reserve strength to be considered.

Nonlinear dynamic response is investigated in the time domain through a step-by-step integration of the equations of motion. Dynamic equilibrium is enforced at successive time increments and the properties of the system are updated continuously according to the current displaced configuration. An explicit integration method, coupled with lumped mass and a mass-proportional damping approach, results in diagonal mass and damping matrices. Thus, the governing equilibrium equations are uncoupled, and the solution can be handled by solving one degree of freedom (DOF) separately. Since the global stiffness matrix is not assembled, abrupt boundary condition changes, e.g. broken wires, can be easily introduced during the analysis.

Two validation case studies are presented. The first assesses the modelling of post-elastic behaviour of steel lattice towers using the proposed technique. A 275 kV double-circuit transmission tower that failed during static full-scale test and was numerically investigated by Albermani et al. [21] is used for this purpose. The second case study verifies the suitability of the developed analysis technique for predicting the response of transmission line sections under loads induced by a broken conductor and a broken insulator assembly. For this case, the full-scale tests conducted by Peyrot et al. [8] on a decommissioned 138 kV line in Wisconsin (USA) are simulated and the response is compared with the results from the full-scale test.

2. Structural system

Each line section is simulated as a group of three basic types of substructure: conductor and shield-wire spans, supports (freestanding and guyed towers) and insulator sets. In turn, each substructure is formed by an assembly of basic elements: tension-only (insulators), cable (conductor and shield wire spans, as well as guys), and beam-column and truss (lattice supports) elements. Insulator assemblies are modelled as a set of short tension-only link elements, which are a particular case of truss elements that exhibit only tensile internal forces [3].

A cable element based on catenary relationships was developed to incorporate the geometric nonlinear behaviour of cable substructures. Its formulation assumes a linear elastic constitutive model, suitable for dynamic analysis [3]. The algorithm can handle uniform loads applied along the length of the element, such as gravity, wind actions and thermal effects. Considering these applied loads and positions of cable end points, the entire geometry of the element is defined, and its end forces are calculated. The equilibrium configuration of element is obtained using an iterative scheme, where the actual horizontal and